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STRENGTH RETENTION AND CORROSION RESISTANCE OF GRAPHITE/EPOXY-ALUMINUM HONEYCOMB SANDWICHES IN SALT SPRAY AND HIGH HUMIDITY ENVIRONMENTS

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by

10 R. E. Mauri [redacted] M. Duggan (Orgn. 52-33)
Materials and Structures Laboratory

LOCKHEED PALO ALTO RESEARCH LABORATORY
LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

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LOCKHEED PALO ALTO RESEARCH LABORATORY
LOCKHEED MISSILES & SPACE COMPANY, INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

SUMMARY

Honeycomb sandwich panels of various types fabricated of aluminum and graphite/epoxy composite facings bonded to aluminum and phenolic fiberglass (HRD) cores were subjected to 30-day accelerated aging exposures to high humidity (95% RH) and salt spray environments. Sandwiches were tested for flatwise tensile and flexural strength before and after environmental aging. In addition, weight loss determinations and visual examination of corrosion effects were performed. Severe galvanic corrosion was found on graphite/epoxy-aluminum core sandwiches during and after the salt spray exposure, and mechanical strength retention was drastically reduced. Those sandwiches made of graphite/epoxy-aluminum core incorporating a 5-mil-thick glass fabric interliner in the core-to-face bonds (between the facings and the modified epoxy adhesive) withstood salt spray exposure extremely well, i.e., no evidence of galvanic corrosion or significant reduction of mechanical strength properties occurred. None of the sandwich types tested were affected by the 30-day 95% relative humidity exposure at 120°F.

Section 1
OBJECTIVES

1.1 To determine the mechanical strength retention of honeycomb sandwiches fabricated of graphite/epoxy composite and aluminum facings, bonded to aluminum and phenolic fiberglass (HRP) cores after exposure to accelerated aging conditions of high relative humidity (95%) and salt spray at elevated temperatures to 120°F.

1.2 To determine the effects of humidity and salt spray aging exposures on the corrosion susceptibility of honeycomb sandwiches of various materials of construction, and, particularly, to establish the degree of galvanic corrosion occurring in composite-to-metal bonded sandwiches (i.e., graphite/epoxy facings and aluminum honeycomb core).

1.3 To determine the relative effectiveness of selected materials and methods for corrosion protection of honeycomb sandwiches during environmental aging. These include elastomeric edge sealants containing corrosion inhibitors and thin layers of glass fabric incorporated into the core-to-face bonds to isolate dissimilar and potentially electrochemically active surfaces.

Section 2

SCOPE OF THE INVESTIGATION

2.1 This experimental program consisted of the testing and evaluation of the mechanical properties, i.e., flatwise tensile strength and 3-point flexural beam shear strength, of six types of honeycomb-sandwich panels before and after exposure to two accelerated aging conditions and three applied stress levels. All honeycomb panels were fabricated and submitted for testing by Orgn. 47-01. Panels were furnished as pre-cut specimens. The construction was reported to consist of the following materials, fabricated under the given conditions.[1,2]

Type "A" - Graphite/epoxy facings (0.020", Type Thornel T 300/X 934) and aluminum honeycomb core (Hexcel 1/4" thick, 1/8" 5056 CR III, 4.5 PCF) bonded with AF-143 modified epoxy adhesive (3M Co.) and cured at 50 psi/350°F.

Type "A2" - Same as Type "A" except that separator interlayers of 0.002"-thick glass fabric were incorporated into both core-to-face bonds (between facings and the adhesive).

Type "C" - Graphite/epoxy facings (0.020", Type Thornel T300/X934) and Phenolic/fiberglass core (Hexcel 1/4" thick, 3/16" HRP, 6.5 PCF) bonded with AF-143 adhesive and cured at 50 psi/350°F.

Type "E" - Aluminum facings and aluminum honeycomb core (1/4" thick, 1/8"-5056 CR III, 4.5 PCF) bonded with AF-143 adhesive and cured at 50 psi/350°F.

Type "J" - Graphite/epoxy facings (0.020", Type Thornel T300 5208) and aluminum honeycomb core (1/4" thick, 1/8"-5056 CR III, 4.5 PCF) incorporating Type 120 glass fabric (0.005" thick) interliner in both core-to-face bonds) and bonded with AF-143 adhesive at 100 psi/350°F.

Type "I" - Same as Type "J" except that no glass fabric separators (interlayers) were incorporated into the bond lines.

2.2 Accelerated aging conditions adopted for the evaluation program were those specified in Federal Test Specification MMM-A-132[3] as follows:

(a) 30 days exposure to 5% salt spray at 95°F ± 5

(b) 30 days exposure to 95% Relative Humidity at 120°F ± 5

2.3 Flatwise tensile and 3-point flexural beam shear tests were performed on specimens before and exposure to both environments. In addition, tests were performed after the high humidity aging exposure on specimens pre-stressed in flatwise tension and flexure. Pre-stressing levels were as follows:

2.3.1 Flatwise tensile stress - 40% of the average ultimate flatwise tensile strength at ambient room temperatures of unaged control specimens (constant stress test).

2.3.2 Flexural beam shear stress - 25% and 50% of the average ultimate 3-point flexural beam shear strength at room temperature of unaged control specimens (constant strain test).

2.4 Test specimens of each type were aged and tested with and without the sandwich edges sealed (to provide a moisture barrier and reduce possible corrosion) utilizing an elastomeric sealant.

2.5 Weight change measurements were made on all specimens subjected to environmental aging by weighing before and after each exposure.

2.6 Observations were made of the type and extent of corrosion occurring on specimens after each environmental exposure. Qualitative rankings of the relative corrosion resistance and effectiveness of corrosion protective materials and methods of construction were established.

Section 3
INTRODUCTION

Several material combinations and configurations of honeycomb sandwich constructions are actively being studied by Orgn. 81-12 as candidates for the preliminary design and fabrication of the equipment section of the Trident I (C-4) missile body structure. Among the most promising types of sandwiches under consideration from the structural and weight standpoints are those consisting of graphite/epoxy composite facings bonded to aluminum or phenolic/fiberglass (HRP) cores. The high strength-to-weight ratio and stiffness of sandwiches fabricated of graphite/epoxy and aluminum core makes this type of sandwich particularly attractive for the intended applications.

Recently performed experimental investigations by Weber et al.[4,5] at the CALAC Rye Canyon Laboratory and by others as reported in the literature (See Bibliography) have shown that serious galvanic corrosion can occur in aluminum alloys and other metals in contact with carbon and graphite fiber reinforced composites, especially under environmental conditions of high relative humidity and/or salt spray. The galvanic corrosion is the result of an electrolytic reaction with a strong driving force, i.e., the large E.M.F. generated by the aluminum-carbon couple. It has been shown that even if the surfaces are not directly in contact with each other, but close together, that the presence of an electrolyte between the surfaces, such as salt water generally results in galvanic corrosion of the aluminum.

Although many such examples of galvanic corrosion have been cited in the literature, mainly on mechanically fastened surfaces, insufficient information has been found on the corrosion susceptibility of graphite/epoxy-aluminum honeycomb sandwiches exposed to accelerated aging conditions of high humidity and salt spray. Because the honeycomb core is bonded to the facings with a non-conductive adhesive film (typically a modified epoxy), it has been questioned whether significant galvanic corrosion could occur. It has been argued that anode and cathode are electrically isolated from each other by the adhesive and, therefore, no electrolytic path could exist(except at the cut edges of a sandwich or through voids and pinholes in the adhesive film). In the absence of direct experimental evidence, however, this experimental investigation was conceived and executed to provide the necessary design and environmental test data.

In addition to graphite/epoxy-aluminum honeycomb sandwiches, panels constructed of graphite/epoxy facings bonded to phenolic/fiberglass core and aluminum facings to aluminum core were included in the test program to obtain comparative mechanical strength retention data and, where applicable, relative corrosion resistance or susceptibility. The program also included an investigation of protective materials and fabrication methods to minimize or eliminate possible galvanic corrosion of honeycomb panels. These consisted of the incorporation of inert separator films, i.e., glass fabric interlayers in the core-to-face bond lines of the sandwiches and the sealing of the exposed sandwich edges with an elastomeric polysulfide sealant containing corrosion inhibitors.

Section 4

SUMMARY OF RESULTS

4.1 Severe galvanic corrosion occurs in graphite/epoxy-aluminum honeycomb core sandwiches exposed to salt-spray. Honeycomb cores were destroyed to a depth of 2 to 3 cell thicknesses, i.e., ca. 3/8", at unprotected edges of the sandwich. Mechanical strengths of sandwiches were reduced up to 80 percent and weight losses up to 14%, of the original values of unexposed control specimens after the 30-day salt spray exposure at 95°F.

4.2 None of the honeycomb sandwich types tested were affected by the 30-day 95% Relative Humidity @ 120°F exposure. There was no evidence of any type of corrosion or mechanical strength reduction during or after the exposure. Prestressing of specimens during the exposure to levels of 25% and 50% of their original ultimate flexure strength did not affect the results; i.e., complete strength retention (100%) was obtained after the stress-environment exposure.

4.3 Graphite/epoxy-aluminum sandwiches can be effectively protected from galvanic corrosion in a salt-spray environment by the isolation or separation of the facings and core to prevent direct contact. Interliners of a 5-mil glass fabric (Type 120) incorporated during sandwich fabrication between the facings and the adhesive in the core-to-face bonds gave effective protection from galvanic action. Sandwiches fabricated in this manner retained up to 90% of their original strength after 30-day exposure to salt spray with no evidence of corrosion.

4.4 Edge sealing of sandwiches with an elastomeric polysulfide sealant, PR-1422G, also gave good corrosion protection by minimizing electrolyte ingress into the graphite/epoxy-aluminum interface. Strength retention of edge-sealed sandwiches of this type exposed to the 30-day salt spray environment was about

70% as compared to 25% for unsealed specimens. Protection, however, was not as good as that obtained on sandwiches incorporating the glass fabric interliners in the core-to-face bond lines. Pinholes and voids in the edge-sealant and diffusion of electrolyte through the elastomer limit the usefulness of this method in providing the necessary degree of corrosion protection.

4.5 Sandwiches constructed of aluminum alloy facings bonded to aluminum honeycomb core (Type 5056 CR III) were severely pitted and discolored at the facings surfaces due to inter-granular corrosion in the salt spray environment. However, no evidence of galvanic corrosion between the different alloys of the core and face was found. Strength retention after the 30-day salt-spray exposure ranged from 86 to 111%, the highest retention observed for any sandwich type tested in that environment.

4.6 Graphite/epoxy-phenolic fiberglass core (HRP) sandwiches were not affected in any significant manner by the 30-day 95% R.H. @ 120°F exposure. All strength retention values were 100 percent or more. Higher strengths after exposure occurred on these and all other types of sandwiches exposed to the humidity environment. This is believed to be the result of post-curing of the core-to-face bonding adhesive at the chamber temperature (120°F) during aging.

4.7 Electrical resistance measurements of the various honeycomb sandwich types tested correlated well with the observed corrosion susceptibility and mechanical strength retentions obtained after the salt-spray exposures. Graphite/epoxy-aluminum sandwich specimens incorporating 5-mil glass fabric interliners in the core-to-face bond lines (Type "J") had essentially infinite resistance before and after aging and did not suffer galvanic corrosion. In contrast, those specimens of similar construction types (Types "A" and "A2") having no interliner (or a thinner 2-mil glass fabric type) initially had low resistances, i.e., 13-180 ohms, respectively, and corroded badly during the salt-spray exposure. After removal from the chamber, washing and drying, the resistances increased to a range of from 200 to 9000 ohms for types "A" and "A2" respectively. The increase in resistance is associated with the presence of corrosion products at graphite/epoxy aluminum interfaces.

Section 5
EXPERIMENTAL PROCEDURES

5.1 SPECIMEN PREPARATION AND CONFIGURATIONS

Honeycomb sandwich panels of the types listed in Section 2.1 were prepared and submitted for corrosion testing and evaluation by Orgn. 47-01 in the form of pre-cut tensile and flexural test specimens, each nominally 0.290 x $1\frac{1}{2}$ x $1\frac{1}{2}$ and 0.290 x 1 x 4 inches, respectively. Test specimens were identified and indelibly marked with a code number for subsequent environmental aging and mechanical testing in accordance with Table 1. Duplicate specimens of each type were to be subjected to the same environment and test conditions. In addition to the as-received specimens, duplicate specimens of each type were prepared with the exposed sandwich edges sealed for subsequent environmental aging and testing.

5.2 EDGE SEALING OF SPECIMENS

The exposed edges of duplicate specimens of each type were sealed to minimize ingress of moisture and reduce corrosion. Sealing of the edges was accomplished by troweling the selected elastomeric sealant, PR-1422G, Class B (Products Research and Chemical Corp.) and uniformly covering the exposed cell walls and core-to-face bonds around the perimeter of each specimen. PR-1422G was recommended by the vendor as a good corrosion inhibiting sealant. It consists of a 2-part room temperature vulcanizing (RTV) polysulfide resin incorporating water soluble metal chromate salts used as corrosion inhibitors. Ten parts of resin were thoroughly mixed with one part of accelerator, the mixture traveled on the edges with a spatula, and cured at room temperature for a minimum of 72 hours before environmental exposure. Sealed specimen types are listed in Table 1 and are typically shown in Figure 1.

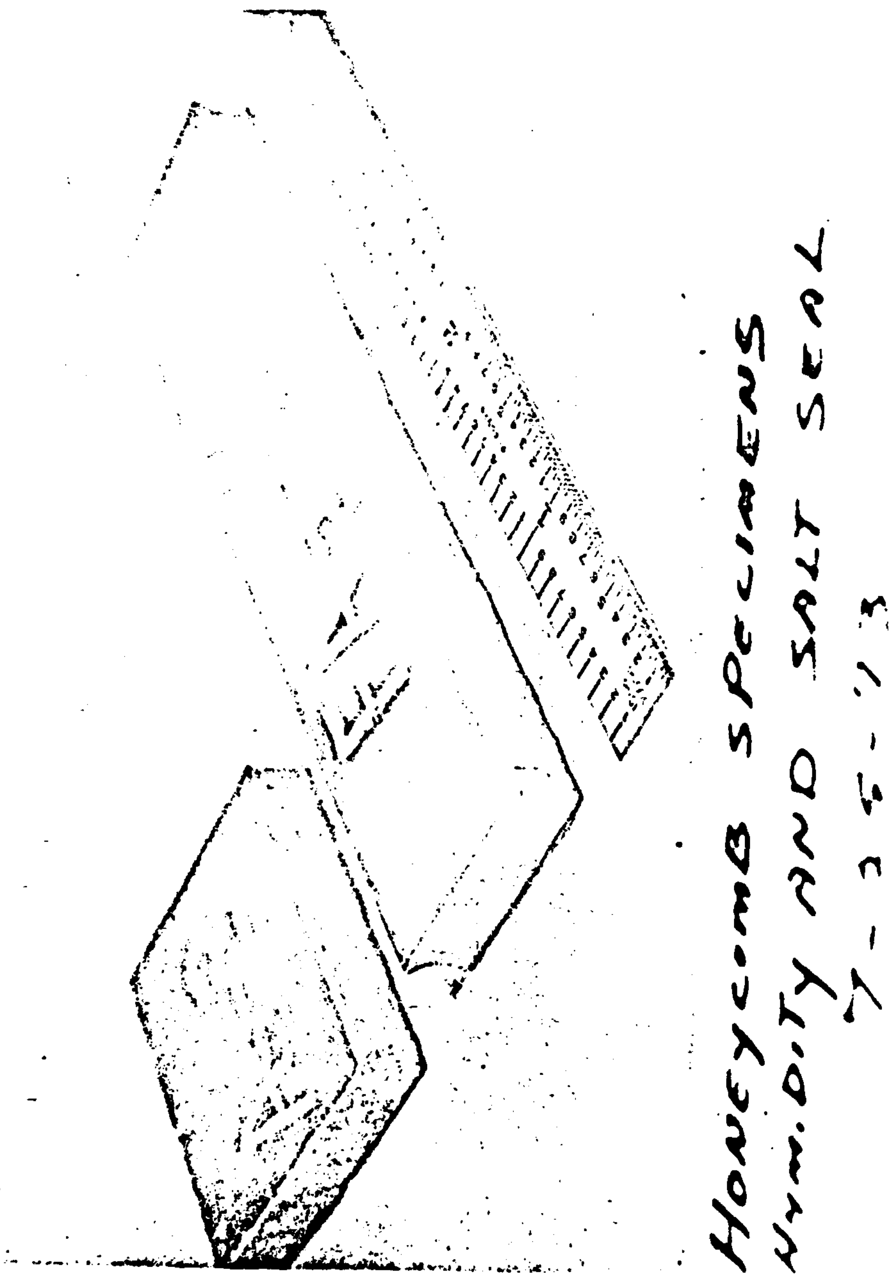

Figure 1. Honeycomb sandwich test specimens with edges sealed with PR-1422G polysulfide elastomer.

Table 1. TEST-ENVIRONMENT SPECIMEN MATRIX

A. Tensile Specimens

Sandwich Type	Specimen Number	Environmental Condition	No. of Specs. With Edges Unsealed	No. of Specs. With Edges Sealed	No. Spec. Tests
"A"	-1, -2	Salt Spray	2	-	2
	-3, -4	Salt Spray	-	2	2
	-5, -6	95% RH, 50% σ	2	-	2
	-7, -8	95% RH, 50% σ	-	-	-
	-9, -10	Controls	2	-	2
Total			6	2	8
"A2"	-1, -2	Salt Spray	2	-	2
	-3, -4	Salt Spray	-	2	2
	-5, -6	95% RH, 50% σ	2	-	2
	-7, -8	95% RH, 50% σ	-	-	-
	-9, -10	Controls	2	-	2
Total			6	2	8
"C"	None →				
"E"	-1, -2	Salt Spray	2	-	2
	-3, -4	Salt Spray	-	2	2
	-5, -6	95% RH, 50% σ	2	-	2
	-7, -8	95% RH, 50% σ	-	2	2
	-9, -10	Controls	2	-	2
Total			6	4	10
"I"	-9, -10	Controls	2	-	2
Total			2	0	2
"J"	-1, -2	Salt Spray	2	-	2
	-3, -4	Salt Spray	-	2	2
	-9, -10	Controls	2	-	2
Total			4	2	6
GRAND TOTALS, TENSILE TESTS			24	14	38

Table 1 (continued)

B. Flexure Specimens

Sandwich Type	Specimen Number	Environmental Condition	No. of Specs. With Edges		No. Spec. Tests
			Unsealed	Sealed	
"FA"	-1, -2	Salt Spray	2	-	2
	-3, -4	Salt Spray	-	2	2
	-5, -6	95% RH, 25% σ	2	-	2
	-7, -8	95% RH, 25% σ	-	2	2
	-9, -10	95% RH, 50% σ	2	-	2
	-11, -12	95% RH, 50% σ	-	2	2
	-19, -20	Controls	2	-	2
Total			8	6	14
"FA2"	-1, -2	Salt Spray	2	-	2
	-3, -4	Salt Spray	-	2	2
	-5, -6	95% RH, 25% σ	2	-	2
	-7, -8	95% RH, 25% σ	-	2	2
	-9, -10	95% RH, 50% σ	2	-	2
	-11, -12	95% RH, 50% σ	-	2	2
	-19, -20	Controls	2	-	2
Total			8	6	14
"FC"	-5, -6	95% RH, 25% σ	2	-	2
	-7, -8	95% RH, 25% σ	-	2	2
	-9, -10	95% RH, 50% σ	2	-	2
	-11, -12	95% RH, 50% σ	-	2	2
	-19, -20	Controls	2	-	2
Total			6	4	10
"FE"	-1, -2	Salt Spray	2	-	2
	-3, -4	Salt Spray	-	2	2
	-5, -6	95% RH, 25% σ	2	-	2
	-7, -8	95% RH, 25% σ	-	2	2

Table 1 (continued)

B. Flexure Specimens

Sandwich Type	Specimen Number	Environmental Condition	No. of Specs. With Edges Unsealed	No. of Specs. With Edges Sealed	No. Spec. Tests
"FE"	-9, -10	95% RH, 50% σ	2	-	2
(cont'd)	-11, -12	95% RH, 50% σ	-	2	2
	-19, -20	Controls	2	-	2
Total			8	6	14
"FI"	-5, -6	95% RH, 25% σ	2	-	2
	-7, -8	95% RH, 25% σ	-	2	2
	-9, -10	95% RH, 50% σ	2	-	2
	-11, -12	95% RH, 50% σ	-	2	2
	-19, -20	Controls	2	-	2
Total			6	4	10
"FJ"	-1, -2	Salt Spray	2	-	2
	-3, -4	Salt Spray	-	2	2
	-5, -6	95% RH, 25% σ	2	-	2
	-7, -8	95% RH, 25% σ	-	2	2
	-9, -10	95% RH, 50% σ	2	-	2
	-11, -12	95% RH, 50% σ	-	2	2
	-9, -20	Controls	2	-	2
Total			8	6	14
GRAND TOTALS, FLEXURE TESTS			44	32	76

5.3 WEIGHING

Each test specimen was weighed before and after exposure to the humidity and salt spray environments to determine weight change. Weights were determined to an accuracy of ± 0.2 grams. After environmental exposure, salt spray specimens were washed in tap water to remove encrusted salt and contaminants and dried thoroughly before reweighing.

5.4 PRE-STRESSING OF SPECIMENS DURING HUMIDITY EXPOSURE

5.4.1 Flatwise Tensile Specimens

A total of eight (8) specimens comprising replicates of Types "A", "A2" and "E" were subjected to pre-stressing in the flatwise tensile direction during the 30-day environmental exposure to 95% R.H. at 120°F. The load applied on each specimen corresponded to 40% of the lowest observed average estimate flatwise tensile strength of any of the unaged control specimens previously tested. The load was applied by means of a specially designed whiffle-tree apparatus as illustrated in Figure 1. The arrangement of the specimens around the hydraulic ram provides for loading of the specimens in parallel, i.e., the total applied load from the ram is shared equally by each of the eight specimens. The power source for the ram is a 5-gallon, 3000 psi accumulator which operated at full rated capacity and included a hand pump capable of recharging any leaks in the system. Each specimen is restrained upon failure by a small crossbar to preclude load imbalance and deviation from the desired stress level. Load transfer to each specimen was accomplished by a pair of aluminum blocks, each nominally 3/4" x 1½" x 1½", and bonded to the sandwich facing surfaces with a room temperature curing epoxy adhesive. The specimens and bonded loading blocks were then attached to the whiffle tree by bolting in place as shown in Figure 2. The entire apparatus was designed to fit within the humidity chamber. The hydraulic ram on the whiffle tree was operated by controls outside the humidity chamber.

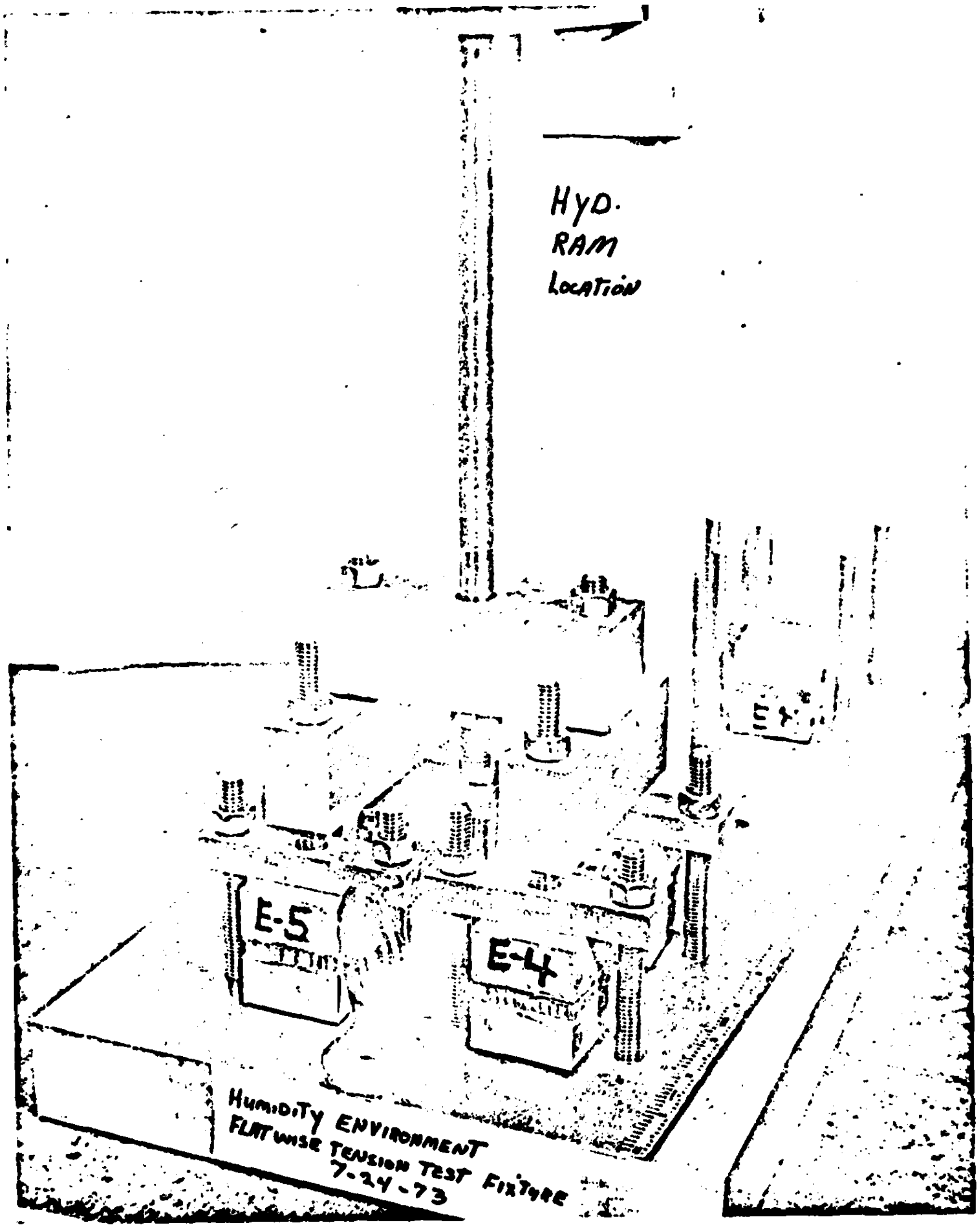

Figure 2. Whiffle tree loading fixture for flatwise tensile tests on honeycomb sandwiches exposed to 95% Relative Humidity Environment.

5.4.2 Flexure Specimens

Figure 3 illustrates the configuration of the flexural loading fixtures utilized to stress duplicate test specimens of each type during the 30-day humidity exposure. Specimens were stressed to 25% and 50% of the average ultimate flexural strength of their respective unaged control specimens. Loading was accomplished by turning the two bolts on each fixture to obtain the same mid-span deflection in the specimen corresponding to the required load. This was determined by calibration of the fixtures against a mechanical testing machine. Corrections for the deflection of the fixtures was taken into consideration. The accuracy of the calibration method in reproducing the required load is about ± 5%. Flexure specimens were subjected to constant strain during environmental exposure rather than constant stress. The specimen pre-load matrix is presented in Table 1.

5.5 ENVIRONMENTAL EXPOSURE

5.5.1 Salt-Spray

Duplicate specimens of Types "A", "A2", "E" and "J" (See Section 2.1) were subjected to 30-day exposure to 5% salt spray at 95°F ± 5, as specified in Federal Specification MMM-A-132[3]. All specimens were unstressed during this exposure. The salt spray chamber used was in the Orgn. 85-81 environmental test facility. Test specimens were suspended within the chamber with wax-coated nylon strings. The temperature of the chamber and the pH of the mist fall-out were measured and controlled daily and weekly, respectively, by Orgn. 85-81 personnel. pH varied from 6.4 to 6.7 and temperatures remained within the required 95° ± 5 during the test duration. See Table 1 for the listing of specimens exposed to salt spray.

5.5.2 Humidity Aging

Humidity exposure of specimens was performed at 95% Relative Humidity (min.) at 120°F ± 3 for 30 days as specified in Federal Specification MMM-A-132.

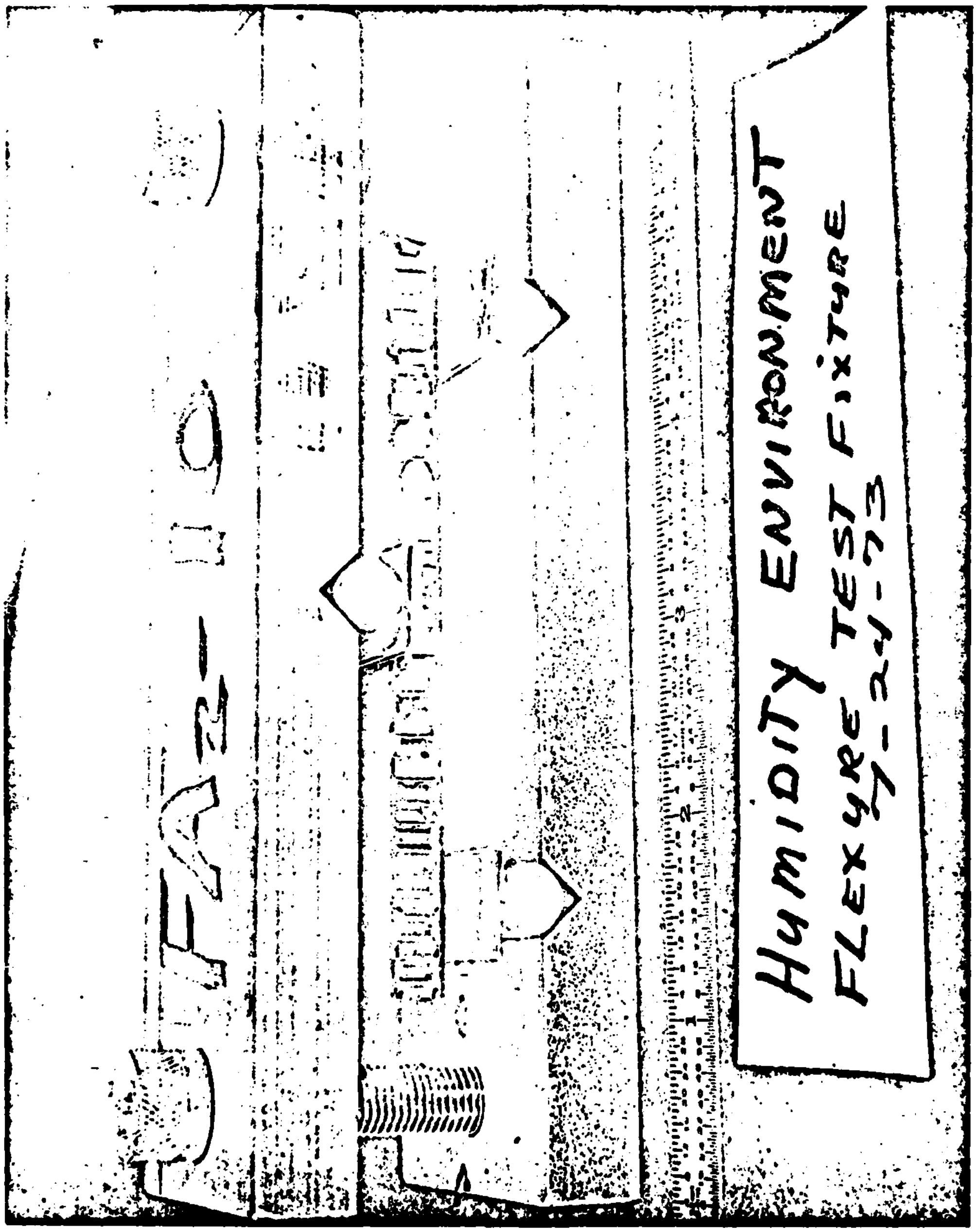

Figure 3. Flexural loading fixture for sandwich specimens exposed to 95% Relative Humidity Environment.

Orgn. 85-81 furnished the environmental test chamber (Chamber USN # 152709). Pre-loaded test specimens in the previously described whiffle-tree apparatus (Section 5.4.1) and the 3-point flexural loading fixtures (Section 5.4.2) were supported on wire racks at chamber mid-height to allow uniform exposure from all directions for the duration of the test. Daily monitoring of temperature and Relative Humidity was performed by Orgn. 85-81 to ensure that test conditions were maintained as specified. No deviations were reported.

5.6 POST-ENVIRONMENT TREATMENT

Specimens were removed from the high humidity and salt-spray environments after 30 days exposure, removed from the pre-stressing fixtures (i.e., flexure) and inspected for evidence and degree of corrosion incurred. These observations were recorded for each specimen tested. Salt-spray specimens were then washed in water and dried before reweighing as previously discussed in Section 5.3. Humidity test specimens were allowed to dry before reweighing (no cleaning).

5.7 MECHANICAL TESTING

After conclusion of the 30-day humidity and salt-spray exposures, specimens were tested for flatwise tensile and 3-point flexural beam shear strength. Pre-loaded specimens were removed from the loading fixtures. The flatwise tensile specimens did not survive the pre-load during the humidity exposure as discussed in Section 4.1.3. Flatwise tensile and 3-point flexural beam shear tests were performed on unaged control specimens and pre-stressed and unstressed specimens exposed to humidity and salt spray in accordance with the procedure given in the following sections. Table 1 presents the matrix of specimen types tested.

5.7.1 Flatwise Tensile Strengths

Unstressed aged specimens (only those exposed to salt spray survived this stage of the test program) and controls were bonded to pairs of aluminum loading blocks each 3/4" x $1\frac{1}{2}$" x $1\frac{1}{2}$", with a room-temperature curing epoxy adhesive in the same manner as has been described in Section 5.4.1 for pre-stressed specimens. Bonded specimens were tested in flatwise tension on a universal testing machine (Wiedemann-Baldwin, 20,000-pound capacity) accurate to a load of ± 0.5% of full scale) at a loading rate of 600 lb/min. Failed specimens were examined for the mode of failure, i.e., delamination of the facings, or core-to-face bond, and the observations were recorded on the basis of the percentage of each mode of failure occurring on each test specimen.

5.7.2 Ultimate Three-Point Flexural Beam Shear Strength

Pre-stressed and unstressed specimens and controls were tested in three point bending (flexural beam shear) to ultimate failure. The configuration of the test fixture was of the same type as that used for pre-stressing the specimens (See Figure 3). The span lengths are also given by Figure 3. Loading was applied with a Wiedemann-Baldwin testing machine at a rate of 600 lb/min. All specimens failed in the core-shear mode. Flexural beam core shear strength of each specimen was calculated from the following relationship:

$$S = \frac{P_s}{(d + t_c)b} \qquad \text{(Ref. 6)}$$

where S = core shear stress

P_s = total applied load

b = sandwich width

d = total sandwich thickness

t_c = core thickness

Section 6
RESULTS

Table 2 summarizes the results of the experimental program and includes the weight changes and mechanical strength retention properties of the various sandwich types exposed to the 30-day salt-spray and 95% Relative Humidity environments. Results of flatwise tensile and 3-point flexural beam shear tests are based on the ratio of the observed ultimate strength after aging relative to the ultimate strength of comparable sandwiches before aging, i.e., the control specimens. Significant visual observations are also included in the Table.

Tables 3-7 present the raw mechanical test data for individual specimens before and after exposure to salt spray and humidity.

Table 2. SUMMARY OF EFFECTS OF 30-DAY SALT-SPRAY AND 95% RH ENVIRONMENTS ON HONEYCOMB SANDWICHES

Sandwich Type	Flatwise Tensile Specimens* Weight Change (%) Unsealed	Flatwise Tensile Specimens* Weight Change (%) Sealed	Flatwise Tensile Specimens* Strength Retention (%) Unsealed	Flatwise Tensile Specimens* Strength Retention (%) Sealed	3-Point Flexure Specimens* Weight Change (%) Unsealed	3-Point Flexure Specimens* Weight Change (%) Sealed	3-Point Flexure Specimens* Strength Retention (%) Unsealed	3-Point Flexure Specimens* Strength Retention (%) Sealed	Visual Observations and Remarks
ENVIRONMENT: SALT SPRAY (30 DAYS)									
"A" (1)	-13.9	- 9.6	25.5	68.0	-10.3	-3.6	20.6	88.5	(1) Severe galvanic corrosion; 2-3 cell walls destroyed around sandwich edges. Sealed specimen was in better condition.
"A2" (2)	-13.7	- 9.9	45.0	76.5	- 9.0	-3.6	71.3	92.0	(2) Same as "A" except slightly less corrosion. Sealed specimen was in better condition.
"E" (3)	-11.5	---	86.0	100.0	- 6.1	-6.0	96.0	111.0	(3) Severe pitting and discoloration of facings, but no galvanic corrosion of core. Best strength retention of any type.
"J" (4)	- 8.0	-12.2	79.5	71.3	- 6.8	-6.2	89.0	100.0	(4) Excellent corrosion resistance, either sealed or unsealed.
ENVIRONMENT: 95% RH, 25% OF ULTIMATE FLEXURE STRENGTH AS PRE-STRESS (30 DAYS)									
"A"	---	---	---	---	+ 2.4	0.0	103.0	103.0	No corrosion or degradation of strength
"A2"	---	---	---	---	+ 0.6	0.0	102.0	104.0	" " "
"C"	---	---	---	---	+ 2.5	0.0	105.0	105.0	" " "
"E"	---	---	---	---	+ 1.0	+0.4	107.0	107.0	" " "
"I"	---	---	---	---	+ 5.6	+2.4	110.0	102.0	" " "
"J"	---	---	---	---	+ 4.4	+4.8	88.5	97.0	" " "
ENVIRONMENT: 95% RH, 50% OF ULTIMATE FLEXURE STRENGTH AS PRE-STRESS (30 DAYS)									
"A"	---	---	---	---	+ 2.4	0.0	104.0	108.0	No corrosion or degradation of strength
"A2"	---	---	---	---	+ 0.6	0.0	100.0	106.0	" " "
"C"	---	---	---	---	+ 2.5	0.0	102.0	108.0	" " "
"E"	---	---	---	---	+ 1.0	+0.4	109.0	107.0	" " "
"I"	---	---	---	---	+ 5.6	+2.4	107.0	117.0	" " "
"J"	---	---	---	---	+ 4.4	+4.8	93.5	99.0	" " "

* Average of two specimens

Table 3. TEST RESULTS - CONTROL SPECIMENS (FLEXURE)

Specimen Number	Failure Load (Pounds)	Failure Stress (psi)
FA-19	BAD TEST	
FA-20	310	534
Average	310	534
FA_2-19	330	568
FA_2-20	310	534
Average	320	551
FC-19	270	465
FC-20	280	482
Average	275	474
FE-19	160	275
FE-20	140	241
Average	150	258
FI-19	180	310
FI-20	175	302
Average	178	306
FJ-19	200	344
FJ-20	200	344
Average	200	344

Table 4. TEST RESULTS - CONTROL SPECIMENS (FLATWISE TENSION)

Specimen Number	Failure Location (%)			Failure Load (lbs)	Failure Stress (psi)
	Bond*	Core	Skin**		
A-9			100	2965	1320
A-10	50		50	2760	1230
A-11			100	2820	1250
Average				2850	1370
A_2-10			100	3130	1390
A_2-11	50		50	3150	1400
Average				3140	1400
E-9	100			3250	1440
E-10	100			3450	1530
E-11	100			3435	1525
Average				3340	1500
I-9			100	2555	1135
I-10		100		2880	1280
Average				2720	1210
J-9			100	----	----
J-10			100	2545	1130
Average				2545	1130

* Refers to the core-skin bond

** Skin interlayer delamination

Table 5. TEST RESULTS - POST SALT-SPRAY ENVIRONMENT (FLATWISE TENSION)

Specimen Number	Sealed	Un-Sealed	Failure Location (%)			Failure Load (lbs)	Failure Stress (psi)
			Bond	Core	Skin		
E-1		x	50	50		2840	1260
E-2		x	95	5		2960	1320
E-3	x				50*	3400	1510
E-4	x		100			3330	1480
A-1		x	100			760	340
A-2		x	100			780	350
A-3	x		50		50	2020	900
A-4	x		50		50	2160	960
A_2-1		x	33	33	33	1500	670
A_2-2		x		20	80	1320	590
A_2-3	x				100	2240	1000
A_2-4	x				100	2560	1140
J-1		x			100	2290	1020
J-2		x			100	1760	780
J-3	x				100	2060	910
J-4	x				100	1580	700

* Part of the failure observed was in the epoxy bonding the specimen to its loading block.

Table 6. TEST RESULTS - POST SALT-SPRAY ENVIRONMENT (FLEX)

Specimen Number	Sealed	Unsealed	Failure Load (Pounds)		Failure Stress (psi)	
FA-1		x	63		109	
FA-2		x	65		112	
FA-3	x		64	252	111	435
FA-4	x			295		508
				274		472
FA_2-1		x	195		337	
FA_2-2		x	261		450	
FA_2-3	x		228	335	393	578
FA_2-4	x			252		436
				294		508
FE-1		x	143		247	
FE-2		x	145		250	
FE-3	x		144	170	249	293
FE-4	x			163		281
				167		288
FJ-1		x	170		294	
FJ-2		x	185		319	
FJ-3	x		178	206	307	356
FJ-4	x			199		344
				203		350

Table 7. TEST RESULTS - POST HUMIDITY ENVIRONMENT SPECIMENS (FLEX)

Specimen Number	Edges Sealed	Edges Unsealed	σ_{MAX} 25%	σ_{MAX} 50%	Failure Load (lbs)		Failure Stress (psi)	
FA-5		x	x		315		543	
FA-6		x	x		324		559	
FA-7	x		x		320		553	
FA-8	x		x		322		555	
FA-9		x		x	320	319	553	550
FA-10		x		x		328		566
FA-11	x			x		335		578
FA-12	x			x		332		555
						329		568
FA-5		x	x		331		571	
FA-6		x	x		323		557	
FA-7	x		x		320		553	
FA-8	x		x		348		600	
FA-9		x		x	331	320	571	553
FA-10		x		x		317		547
FA-11	x			x		336		579
FA-12	x			x		342		590
						329		568
FA-5		x	x		285		491	
FA-6		x	x		294		507	
FA-7	x		x		293		505	
FA-8	x		x		285		492	
FA-9		x		x	289	275	498	474
FA-10		x		x		287		495
FA-11	x			x		292		504
FA-12	x			x		303		523
						289		497
FA-5		x	x		160		276	
FA-6		x	x		160		276	
FA-7	x		x		165		285	
FA-8	x		x		158		272	
FA-9		x		x	161	158	278	272
FA-10		x		x		170		293
FA-11	x			x		160		276
FA-12	x			x		160		276
						162		280

Table 7 (continued)

Specimen Number	Edges: Sealed	Edges: Unsealed	σ_{MAX} 25%	σ_{MAX} 50%	Failure Load (lbs)		Failure Stress (psi)	
FA-5		x	x		195		336	
FA-6		x	x		195		336	
FA-7	x		x		185		319	
FA-8	x		x		180		310	
FA-9		x		x	189	198	326	341
FA-10		x		x		182		314
FA-11	x			x		213		367
FA-12	x			x		205		353
						199		343
FA-5		x	x		178		307	
FA-6		x	x		176		303	
FA-7	x		x		185		319	
FA-8	x		x		203		350	
FA-9		x		x	186	178	321	307
FA-10		x		x		196		332
FA-11	x			x		207		357
FA-12	x			x		180		328
						193		333

Section 7
DISCUSSION OF RESULTS

7.1 VISUAL OBSERVATIONS OF CORROSION SUSCEPTIBILITY

7.1.1 Humidity Exposed Specimens

No visible evidence of corrosion was found among the various types of honeycomb sandwich specimens exposed to the high humidity (95% RH) aging condition.

7.1.2 Salt Spray Exposed Specimens

Honeycomb sandwiches fabricated of aluminum core and graphite/epoxy facings (Type "A") exhibited severe galvanic corrosion in salt spray. Up to three rows of core cells were destroyed at the unsealed exposed edges of the sandwiches. Those specimens of graphite/epoxy incorporating the 5-mil-thick, Type 120, glass fabric in the core-to-face bond liner (Type "J") did not show any galvanic or other type of corrosion whatsoever (see Figure 4). In contrast, specimens of similar construction incorporating a thinner (2 mil) glass fabric separator (Type "A2") corroded to almost the same extent as the Type "A" specimens (see Figure 5). Aluminum-to-aluminum core sandwiches (Type "E") did not show galvanic corrosion of the core, but were severely pitted and discolored on the facings, probably due to intergranular corrosion, after salt-spray exposure (see Figure 6).

7.1.3 Prestressed Specimens

Test specimens pre-stressed to the 25% and 50% values of the ultimate unexposed (control) flexural beam shear strength and maintained at constant initial deformation (strain) during the 30-day humidity exposure did not fail at these stress levels. Specimens pre-stressed to 40% of the ultimate flatwise tensile strength and maintained at constant stress during the same

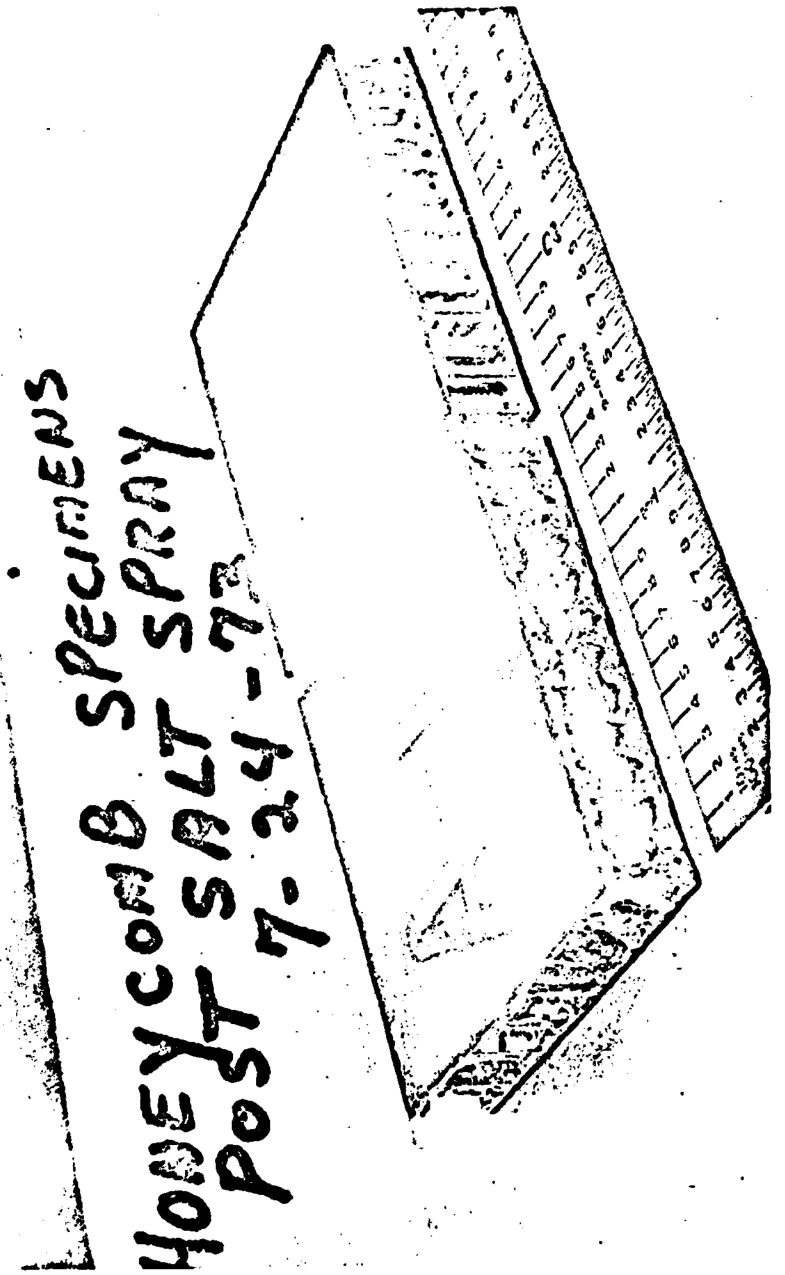

Figure 4. Graphite/epoxy-aluminum core honeycomb sandwiches after 30-day salt spray expsoure showing extents of galvanic corrosion.

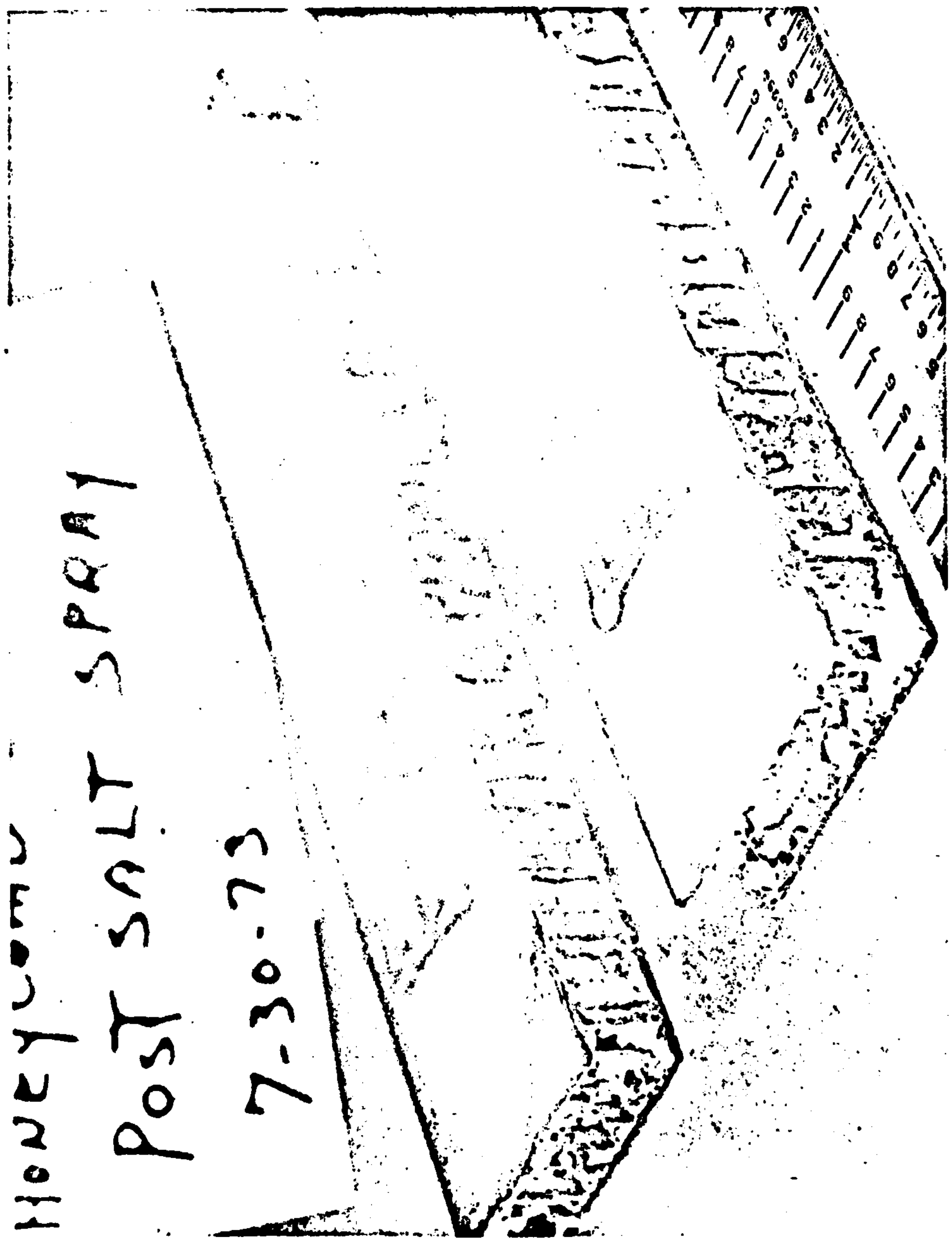

Figure 5. Graphite/epoxy-aluminum core honeycomb sandwiches after 30-day salt spray exposure showing effects of galvanic corrosion.

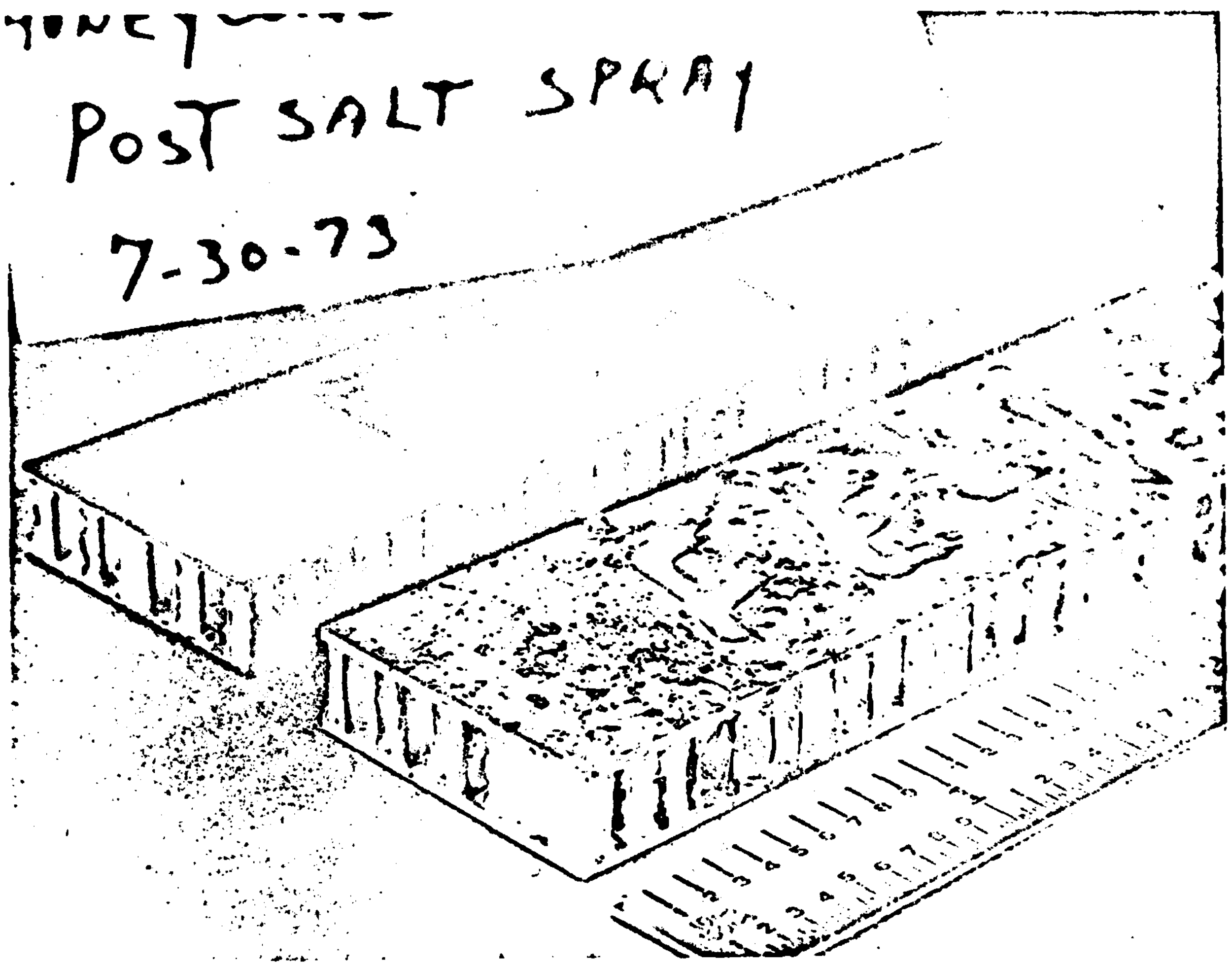

Figure 6. Graphite/epoxy-aluminum core honeycomb sandwich (FJ-1) and aluminum-aluminum core sandwich after 30-day salt-spray exposure showing effects of corrosion.

humidity exposure conditions all failed within the first 7 days of the exposure. The modes of failure were of two types: (1) epoxy adhesive failure between the facings and the aluminum loading blocks; and (2) peeling of the top ply of the graphite/epoxy composite facings (interlaminar shear failure of the composite). Test results were therefore invalidated. Consideration was given to reporting these tests after rebonding the blocks with a less moisture-susceptible adhesive and edge sealing to prevent moisture "undercutting". However, these tests were not repeated because of specimen and aging schedule limitations and directives concurrent with that decision from Orgns. 81-12 and 47-01.

7.2 MECHANICAL STRENGTH RETENTION AFTER AGING

7.2.1 Salt-Spray Environment

Except for Type "J", specimens with sealed edges retained flatwise tensile and flexural ultimate strengths better than comparable unsealed specimens after aging 30-days in the salt-spray environment. Relative rankings on the basis of percent strength retention are as follows:

Ultimate Flatwise Tensile Strength

Sealed Specimens		Unsealed Specimens	
Type	% Retention	Type	% Retention
"E"	100.0	"E"	86.0
"A2"	76.0	"J"	79.5
"J"	71.3	"A2"	45.0
"A"	68.0	"A"	25.2

Ultimate 3-Point Flexural Beam Shear Strength

Sealed Specimens		Unsealed Specimens	
Type	% Retention	Type	% Retention
"E"	111.0	"E"	96.0
"J"	100.0 *	"J"	89.0 *
"A2"	92.0	"A2"	71.3
"A"	88.5	"A"	20.6

* The tensile strength retention values of both sealed and unsealed Type "J" specimens were essentially the same. The variation is not considered statistically significant.

Note that all specimen types retained 70% or more of their original ultimate tensile and flexural strengths after exposure to salt spray except for unsealed Types "A" and "A2" specimens. These data, the visual observations of corrosion, and the weight loss data previously reported in Table 1 clearly show that Types "A" and "A2" specimens are unsatisfactory as prepared and tested for salt-spray exposure because of the severe galvanic corrosion and excessive degradation of mechanical properties. Edge sealing of these specimen types, however, reduces the effects of salt-spray aging and increases strength retention values to acceptable levels. See Figure 7 for the extent of corrosion and mode of failure of a typical graphite/epoxy-aluminum specimen (Type "A2").

7.2.2 95% Relative Humidity Environment

Flexural test specimens of all types of construction satisfactorily withstood the humidity aging environment with no significant loss of strength as compared to the respective unaged control specimen ultimate strength values [i.e., $93\% \le \frac{\sigma}{\sigma o}(100) \le 112\%$]. The increases in strength noted after aging are believed to be the result of post-curing of the core-to-face adhesive bond at the aging temperature (120°F). There was no significant effect of the 25% and 50% pre-stresses on the strength retention during and after aging. In fact, specimens at the 50% pre-loads had slightly, though insignificantly,

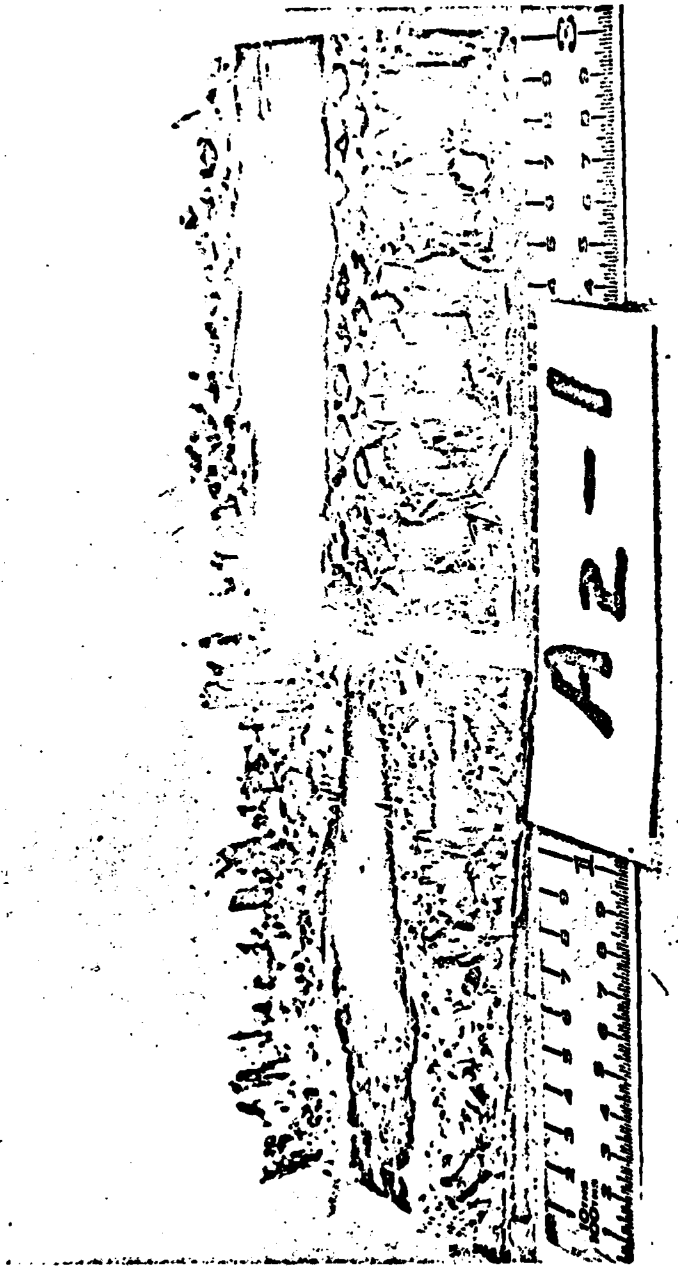

Figure 7. Graphite/epoxy-aluminum core honeycomb sandwich after 30-day salt-spray exposure showing effects of corrosion (flatwise tensile test, specimen removed from loading pad).

greater strength retention than those at the 25% level after aging. See Figures 8 and 9 for the typical modes of failure obtained in flexure (i.e., core shear). Results are as follows:

Specimen Type	Pre-Stress Level	% Strength Retention
"A"	25% of Ult. Control Strength	103
	50% " " " "	106
"A2"	25% " " " "	103
	50% " " " "	103
"C"	25% " " " "	105
	50% " " " "	105
"E"	25% " " " "	107
	50% " " " "	108
"I"	25% " " " "	106
	50% " " " "	112
"J"	25% " " " "	93
	50% " " " "	96.5

Flatwise tensile specimens exposed to humidity aging were subjected to a preload of 40% of their respective ultimate control strengths and failed prematurely as reported in Section 7.1.3. The modes of failure (i.e., delamination of the composite facings and secondary adhesive bond separation to the loading blocks are clearly not caused by corrosion of the sandwiches tested (Types "A", "A2", and "E"). Failures occurred within 7 days after exposure to the humidity environment.

7.2.3 Flatwise Tensile Load Discrepancies

Types "I" and "J" specimens are made of the same types of materials and construction as Types "A" and "A2", respectively. Accordingly, the flatwise tensile and flexural strengths of the unaged control specimens would be expected to be of about the same magnitude in both sets, i.e., "I" and "A" specimens should be of comparable strengths, as should also be the case with "A2" and "J" specimens. Results of mechanical tests on controls, however, show that "I" and "J" control specimens are both about 15% lower in flatwise tension and about 40% lower in flexural strength than the respective "A" and "A2" control specimens. Since "I" specimens contain no glass fabric

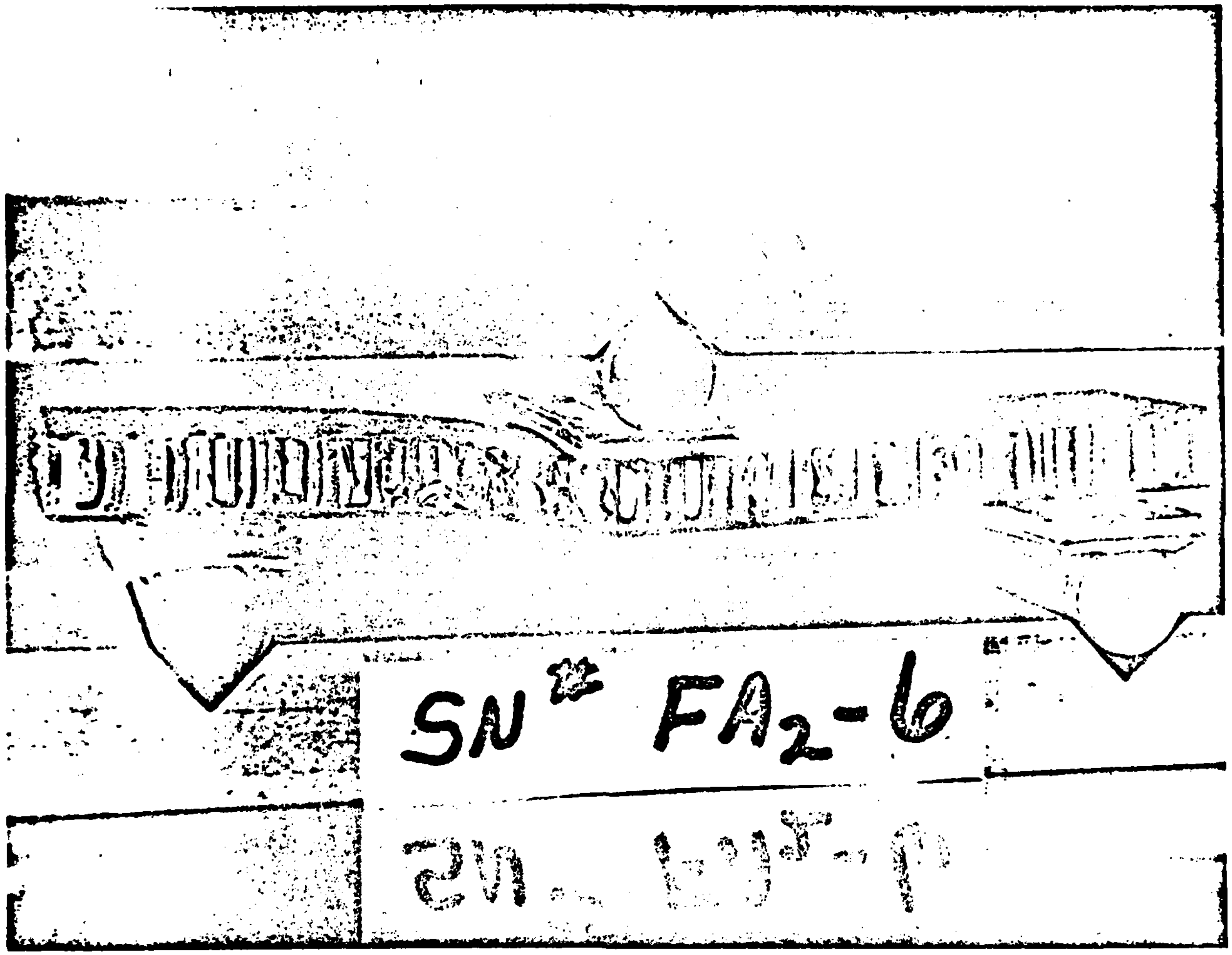

Figure 8. Graphite/epoxy-aluminum core honeycomb sandwich showing mode of failure (i.e., core shear) during 3-point flexure test.

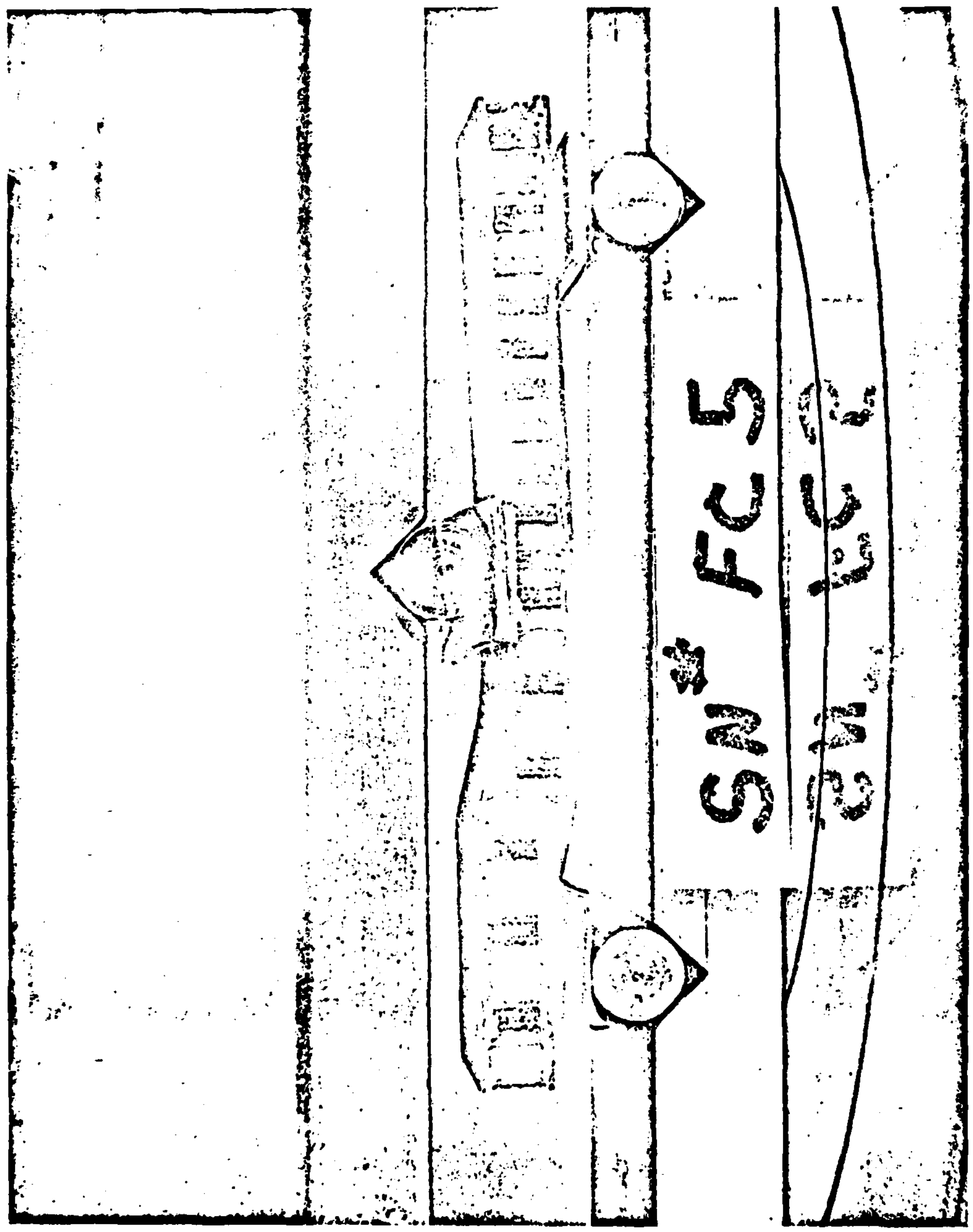

Figure 9. Graphite/epoxy-HRP core honeycomb sandwich showing mode of failure (i.e., core shear) during 3-point flexure test.

interliner in the sandwich core-to-face bonds, whereas "J" contains a 4-to-5-mil, Type 120, glass fabric layer, the differences in strength with the counterpart "A" and "A2" specimens do not appear to be attributable to the difference in materials or construction of the specimens. These differences are believed to arise from variations in the methods of fabrication of the sandwiches including the bonding cure cycle. It has been reported that both "I" and "J" specimens were cured at a higher pressure (100 psi) than "A" and "A2" specimens (50 psi). Another variable which could account for the strength decrease in "I" and "J" specimens is the type of graphite/epoxy composite used in the facings lay-up (Thornel T-300 reinforcement with Narmco #5208 epoxy resin). Types "A" and "A2" specimens were reported[1] to have laminated facings made from Thornel T-300 reinforcement and Fiberite X934 epoxy resin.

7.3 SUMMARY OF EFFECTS OF SALT-SPRAY AND HUMIDITY ENVIRONMENTS ON SANDWICH TYPES

The effects of the aging environments on the properties of the various sandwich types tested are summarized in Table 2. Weight loss, strength retention properties, and visual observations of the extent of corrosion after exposure are included in the Table. Results clearly show that specimen types "E", "J", and "C" are satisfactory for use in salt-spray and high-humidity environments with no evidence of galvanic corrosion and good strength retention values after aging. In contrast, specimen types "A" and "A2" suffered moderate-to-severe degradation of mechanical properties and excessive galvanic corrosion in the salt-spray environment and are not considered satisfactory for use under these test conditions. Edge sealing of these sandwich types to provide a moisture barrier does improve corrosion protection as can be seen from the data of Table 2. However, the presence of pin holes and voids in the sealant has been shown to provide a moisture path which results in excessive localized corrosion and loss of strength in specimen Types "A" and "A2".

Based on these test results, it appears that graphite/epoxy-aluminum core honeycomb sandwiches are galvanically active and incur excessive corrosion when exposed to environments wherein strong electrolytes are present and which can come into contact with the chemically dissimilar and active surfaces. The separation of the anode and cathode with a non-permeable inert and non-conductive layer such as a glass fabric interliner in the core-to-face bonds of the sandwich structure has been shown from the data and observations to be an effective methcd for minimizing or eliminating galvanic corrosion. Type "J" specimens constructed in this manner with a 5-mil, glass fabric interliner do not show evidence of galvanic corrosion whatsoever. In contrast, Type "A2" specimens, which also are reported to contain a glass fabric interliner (albeit a thinner, 2-mil, layer), show excessive galvanic corrosion under the same test conditions. The reason for this difference in behavior is not clearly understood. It is probable, however, that the thinner glass fabric does not effectively electrically isolate the anodic and cathodic surfaces. Indeed, a determination of the electrical resistance across the thickness direction of the sandwich specimens before and after environmental aging clearly shows that specimen types "A" and "A2" have relatively high conductivity (13Ω and 170Ω, respectively) before testing, whereas Type "J" specimens had essentially infinite resistance under the same conditions. Resistance values after salt-spray aging, washing and drying, were significantly greater for Types "A" and "A2" unsealed specimens (200-500Ω and 6.5-9.0KΩ, respectively) as compared to the resistances of the controls. Sandwich specimens of Types "A" and "A2" with sealed edges showed resistances of 13Ω and 1.8KΩ, respectively, after salt-spray exposure. Hence, Type "A2" increased in resistance and Type "A" did not change as compared to the unaged control values. The increase in resistance found can be explained on the basis of the insulating properties of the corrosion products formed at the core-to-face interface as a result of galvanic reaction. Both sealed and unsealed Type "J" specimens retained essentially inifinite resistance after salt-spray aging. Complete results of resistance measurements on specimen Types "A", "A2", "J", and "E" before and after exposure to the salt-spray environment are presented in Table 8.

Resistance tests are, therefore, a meaningful way of determining the likelihood and degree of galvanic corrosion between chemically active surfaces. If

Table 8. ELECTRICAL RESISTANCE OF HONEYCOMB SPECIMENS BEFORE AND AFTER SALT-SPRAY EXPOSURE

Specimen Type	Before Exposure (Control)	After 30-Day Salt Spray *
"A"	13, 13	200, 500
"A2"	180, 160	6500, 9000
"E"	0, 0	0, 0
"J"	∞, ∞	∞, ∞

* Specimens were washed in water to remove encrusted salt and contaminant deposits and dried before measurement of resistance.

the resistance is very large across the panel thickness, no galvanic corrosion will occur (except possibly at the exposed edges where bridging by the electrolyte can complete the circuit). If the resistance is low, however, galvanic corrosion will inevitably occur at such interfaces. The change in resistance in these sandwiches before and after environmental aging is a useful measure of the degree of galvanic corrosion sustained. The rate and degree of corrosion sustained will be influenced by the E.M.F. of the couple, the conductance between the surfaces, and the environment (i.e., temperature and the nature of the electrolyte). From these data and observations, it is concluded that specimen Type "A2" corroded more than the similarly constructed specimen Type "J" because electrical isolation was not complete between the graphite/epoxy facing and the aluminum core (i.e., the glass fabric separator was not of sufficient thickness to insulate the surfaces from each other). Type "A2" specimens, however, corroded less than Type "A" specimens under the same conditions because the interfacial resistance was greater.

Section 8
CONCLUSIONS

8.1 Graphite/epoxy composite-aluminum honeycomb core sandwiches must be protected from serious galvanic corrosion in salt-spray environments.

8.2 Effective corrosion protection methods consist of the separation and insulation of the graphite/epoxy facings from the aluminum core and edge sealing of the sandwiches to prevent ingress of electrolyte.

8.3 Sandwiches fabricated with an inert and non-conductive interliner between the facings and the core (in addition to the film adhesive used for bonding) effectively insulated the graphite/epoxy from the aluminum surface if of sufficient thickness. Those sandwiches incorporating a 5-mil-thick, type 120 glass fabric between the facings and core-to-face adhesive (Type "J") did not show any type of corrosion after 30-day exposure to 5% salt spray at 95°F. Mechanical strength retention of these sandwiches was about 70% in flatwise tension and 90% in flexural beam core shear.

8.4 Sandwiches incorporating a thinner glass fabric, i.e., 2 mils, did not effectively insulate the graphite/epoxy composite from the aluminum core as evidenced by the low resistances obtained in the sandwich thickness direction. These sandwiches (Type "A2") suffered almost as severe galvanic corrosion during salt-spray exposure as sandwiches having no interliner in the core-to-face bond liner (Type "A"). For these types, up to three rows of cells adjacent to the exposed edges of the sandwiches were destroyed by salt-spray induced galvanic corrosion. Mechanical strength properties were reduced up to 80% of their original values.

8.5 Edge sealing of sandiwches with a polysulfide elastomer containing corrosion inhibitors (PR 1422G, Products Research & Chemical Co.) retarded and reduced, but did not eliminate, galvanic corrosion in graphite/epoxy-aluminum core sandwiches exposed to salt spray.

Strength retention of sealed specimens was better than comparable types of unsealed specimens but were not as good as those incorporating the 5-mil glass fabric interliner in the core-to-face bond liner, i.e., Type "J". Moisture ingress through pinholes, voids, and permeation through the graphite/epoxy facings and/or the elastomeric coating resulted in visible, although more localized and reduced degree of corrosion of the cores.

8.6 All sandwich types tested were found suitable for 30-day exposure to 95% Relative Humidity at 120°F and no evidence of any type of corrosion was found, and strength retentions were 100% in all cases.

Section 9
RECOMMENDATIONS FOR FURTHER WORK

9.1 Thicker adhesive films incorporating glass fabric (or other types of reinforcement scrims) may obviate the need for a separate interliner between the facings and the adhesive. It is recommended that graphite/epoxy-aluminum core honeycomb sandwiches bonded with other types and thicknesses of core-to-face adhesive films be prepared and evaluated under salt-spray conditions in accordance with the procedures described herein.

9.2 Evaluate other types of sealants and coatings for corrosion protection of exposed edges of honeycomb panels.

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